Method for estimation of volume damages in composites by usage of acoustic emission criteria

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ABSTRACT: *Using the proposed model for acoustic emission (AE) caused by crack formation in a solid it is found that AE amplitudes are in direct proportion to the crack area. Employing this model experimental AE investigation of damaging in composite materials with various types of carbon fibers stacking are presented. Sixteen layers of carbon fibers placed in the same matrix gave the different durability and AE activity of a loaded composite. Criteria for quantitative assessment of the composite damaging, accounting a specific change in the AE amplitude during the different stages of loading, are developed. The analysis of spectrum characteristics of the AE pulse passed through the perfect and the damaged specimens has confirmed the efficiency of the proposed criteria. Numerical values of the criteria parameters for investigated types of composite specimens are presented.*

INTRODUCTION

One of the specific features of composite materials is that they are frequently created simultaneously with a structure. That is why it is necessary to study the physical and mechanical properties of composites at all stages of their manufacturing [1].

At the beginning of the 70ies in the investigation of fracture processes in composites and non-destructive testing as well as in technical diagnostics of their products a method of acoustic emission (AE) has been used. This method is highly sensitive and allows us to test effectively a structure or its separate elements irrespectively to its shape and size. Naturally, the application of non-destructive testing and technical diagnostics using AE phenomenon requires the establishing of the appropriate correlations between AE signals and the processes of formation and growth of different types of defects nucleated in composites under static or alternating loading. They cause fracture of matrix, fibers, compounds as well as their interfaces. Note that the majority of the known methods of flaw detection widely applied in non-destructive testing and diagnostics of metal products and structures have proved to be unsuitable for researches of composites due to their complex structure [1]. Therefore, development of new criteria and techniques for modern methods of crack detection in composites is of great importance.

AE MODEL OF CRACK FORMATION

Let us consider an infinite homogeneous and isotropic elastic body. At infinity uniformly distributed tensile stress of intensity σ is applied along *Oz* axis. Let us assume that at the time $t = 0$ in the area of a body, where stresses achieve critical value of σ_0, a penny-shaped crack is formed.

The boundary conditions corresponding to a penny-shaped crack formation in cylindrical coordinate system $Or\varphi z$, whose origin *O* coincides with the center of a penny-shaped crack, and axis *Oz* is perpendicular to the crack plane are given in [2].

Analyzing the solution of the problem in paper [2] the approximation expression for estimation of the maximal values of the displacement vector is proposed:

$$u_{\max}\big|_{c_i} = \frac{\beta_i \sigma_0 \Phi_i(\theta) r_0^2}{\rho c_1^2 R}, \tag{1}$$

where functions $\Phi_i(\theta)$ characterize the angular distribution for longitudinal and shear waves, respectively, at $R >> r_0$, R is the distance from the crack area to the observation point, ρ is material density, c_1 is the velocity of longitudinal wave, β_i are the proportionality factors for longitudinal (i=1) and shear (i=2) waves, respectively; β_1=0,45 and β_2=0,82.

In the case when several cracks are formed, we find that the area of new-formed defects can be estimated using the sum of AE amplitudes as follows:

$$S = \gamma \Sigma A_i \tag{2}$$

where A_i is the amplitude of AE signal that is proportional to $u_{\max}\big|_{c_i}$ and γ is AE constant of the material, that takes into account its strength characteristics (elasticity modulus, Poisson's ratio, yield point) as well as AE device modes of AE recording, $i = 1, 2, \ldots m$, m is the number of AE signals recorded during deformation.

AE TEST RESULTS

The laminated composite specimens of width d=20, length q=100 and thickness h=2 mm were investigated. Three groups of composite specimens each having 16 layers of the carbon fibers compounded by similar epoxy matrixes were prepared. In all groups of specimens the layers were stacked according to the specified fiber interlacing [3].

Specimens under three-point bending were tested. The distance between the supports was l=40 mm. A traverse speed of the indenter was 0,02 mm/s. A P-113 serial piezoelectric transducer with a frequency band of 0,1…0,5 MHz was used to detect AE signals. It was mounted at the edge of the specimen behind the supports and pressed with a force of 10…20 N by using a contact layer of oil. AE signals were recorded with an AVN-3 device. The amplification factor in the operating frequency range 0,12…0,5 MHz was equal to 74 dB and the transfer ratio of low and high frequencies filters was approximately equal to 1. In characteristic points of deformation curve the onset of fracture stages in composites as well as critical fracture load and AE signals distribution were determined. The appropriate magnitudes of mechanical values have been found using the curve "specimen deflection f - load P". By increasing the distance between supports the influence of deformation on fracture nucleation in the matrix and fibers, critical stress value corresponding to the onset of macro-cracking were established using AE signals. In all tests the location of the piezoelectric transducer, the device modes of AE signals selection and recording, loading rate and the experiment setup were the same. The maximal values of normal and tangential stresses acting in the cross-section of the specimen at any load were determined by the known formulae. Experimental researches were carried out according to the technique described in [3,4].

Fracture of composites, as well as of any structure material does not occur instantly. Nucleation and subcritical growth of a defect takes the greater part of this process until it reaches the critical sizes. At this moment unstable stage begins resulting in the final failure of material. Note that the period of subcritical defect growth (when the accumulation of volume damages occurs in the material) is the controlling stage of the process. It can be divided into three consequent stages: 1) the beginning of fracture, 2) the latent period when defect influence is yet insignificant on a macrolevel and 3) the critical stage. The last one is mainly short-term and transforms into unstable stage that is very short in comparison with the subcritical stage. Therefore, the diagnostics of composite products needs to be able to distinguish the stages of volume damage accumulation. For this purpose, it is necessary to have criteria of their estimation.

Criterion 1. Latent period of volume damage accumulation in composites begins under condition $\sigma^* \geq \alpha\sigma_{max}$ (α< 1 is AE constant)

The diagrams of specimens loading for all three groups of composites are shown in Figure 1. It follows from Figure 1 that the best strength parameters have the specimens of group II and the best strain parameters have the specimens of group III. The specimens of all three groups have also a different AE activity. It follows from the analysis of AE records.

With the further loading, AE signals, having amplitudes approximately by one order of magnitude higher, begin to emit. We assume this moment corresponds to the beginning of macrocracking in composites, namely to the beginning of fiber bunches failure in composite layers. The mode I stresses, which appear at that moment are denoted by σ^*, and σ_{max} is the corresponding stress at the moment of abrupt fall of loading on the curve *f* - *P* (see Figure 1*a*).

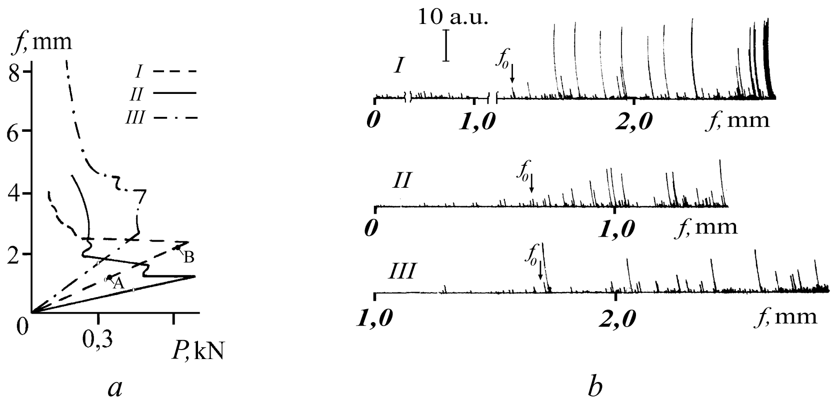


Figure 1: Dependence of deflection *f* on load *P* (I, II, III denote the groups of specimens) (*a*) and typical time distribution of AE amplitudes during quasi-static loading of specimens at the point σ_{max} (f_0 – corresponds to initial phase of volume damages accumulation) (*b*).

The increase of the applied load within the interval from σ^* to σ_{max} is accompanied also by the increase of AE signal amplitudes. It is reasonably to assume, that the ratio $\alpha = \sigma^*/\sigma_{max}$ allows us to quantitatively estimate the latent development of local fracture in the composite. By comparing the experimental data obtained for these three groups of specimens we have found the parameters that describe the latent fracture period in composites. It was different for each group of specimens and the following average magnitudes of parameter *a* were obtained: α_1 = 0,47; α_2 = 0,60 and α_3 = 0,63 for group I, II and III, respectively. Thus, subcritical cracking in composite specimens occurs according to their AE records in the given range of α. Processing of experimental data has shown that the data scattering for the criterion parameter was ±10…20% of its average value. It is caused mainly by deviations of σ_{max} value and in a less degree by the scattering of σ^*. Taking into account this circumstance, we have derived the minimal value of constant α with the maximal scattering of 20 % from the equation $\alpha = (\sigma^*_{i\ min} - 0{,}2\ \sigma^*_{i\ min}) / (\sigma_{i\ max} + 0{,}2\ \sigma_{i\ max})$. Thus we have found that constant α=0,35. The criterion for determination of the beginning of latent development of volume damages in composites of the given type then takes the form:

$$\sigma^* \geq 0{,}35\ \sigma_{max}. \qquad (3)$$

Criterion 2. Critical volume damaging in composites could be determined by inequality $\Sigma A_i / V \geq \xi^*$ (ξ^* is AE constant)

Further analysis of AE signals amplitudes has allowed us to establish another important criterion for quantitative estimation of volume damaging in composites. This criterion accounts the sum of AE signals amplitudes from the moment of the latent period onset to the moment when stresses achieve the value of σ_{max}, i.e. at the subcritical stage of volume damaging development.

As it is shown above, nucleation and development of fracture in structure materials is accompanied by the growth of the surface areas of new-formed discontinuities. The technique for the proposed criterion application is as follows. Firstly, we find the value of ΣA_i (where A_i is the amplitude of m-th AE signal, m = 1, 2,…, m) within the interval from the beginning of AE appearance to the moment of the abrupt loading fall in the f - P curve (the moment of macrocracking), namely, as it was noted previously, when the mode I stresses gets the value of σ_{max}. Then we estimate the volume damaging ξ for each type of specimens by eq. (3). Having these values of ξ for each group of composites, we find their minimum value ξ_i. The analysis of typical AE data for all three groups of specimens recorded to the point, corresponding to σ_{max}, has shown that average values of ξ_i for the specimens with different stacking of carbon fibers were: ξ_1 = 0,25, ξ_2 = 0,1 and ξ_3 = 0,087 a.u./mm^3 for I, II and III groups, respectively. The scattering of the values was within the range ± 8…12%. In this case the minimum value with account of the maximal scattering becomes the AE constant ξ^* that could be estimated by the expression: $\xi^* = \xi_3 - 0{,}12\xi_3 = 0{,}087 - 0{,}12\times0{,}087 \approx 0{,}077$ a.u./mm^3. Hence, in this case the second criterion for estimation of the critical value of volume damages in composite takes the form:

$$\Sigma A_i / V \geq 0{,}077. \quad (4)$$

By comparing the values of ξ for all tested specimens, we have found that groups II and III have shown almost identical tendency to nucleation and development of the failure processes. Group III is the most flexible as it follows from Figure 1*b*. This fact, in our opinion, shows that though there are significant dissimilarities in curves *f* - *P*, the accumulated volume damages in these specimens, however, are close by the value. It stimulated us to estimate the influence of deformation on AE signals. For this purpose, the distance between supports was increased up to 70 mm, and the ratio between the sum of AE amplitudes at the identical specimen deflection and different (significantly less) σ was found. The curve *f* - *P* and amplitude distribution of AE in these tests are shown in Figure 2.

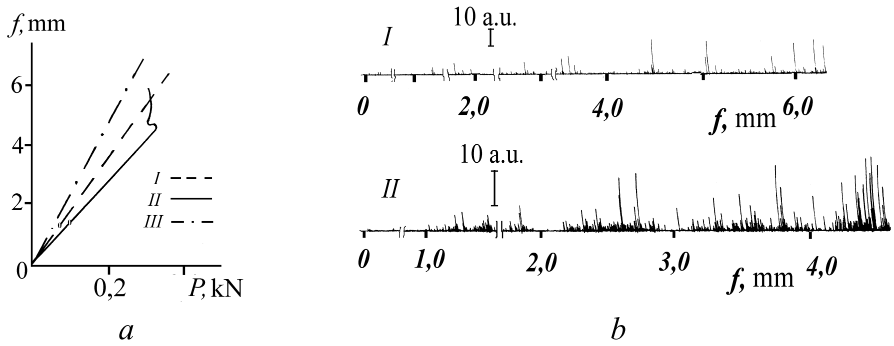
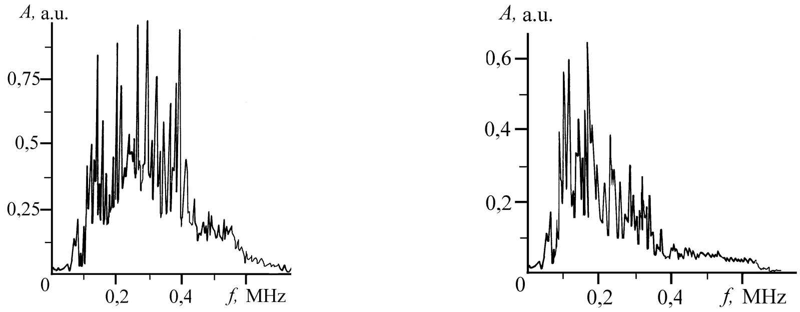


Figure 2: Curve *f-P* (*a*) and corresponding AE distribution (*b*) (in composites of group III no AE signals were observed).

As a result we have found that the influence of deformation on AE processes is within 0…0,1% (group III) and 0,5…4 % (groups I and II) of the total sum of AE amplitudes recorded at the same deflection but at higher σ (at the distance of 40 mm between the supports). Thus, it is established that in our tests the major contribution in AE gives the force factor that causes nucleation and development of micro- and macrocracking.

Criterion 3. The level of subcritical damage accumulation is determined by dependence $S^*_1 \leq S \leq S^*_2$ ($S^*_1 < S^*_2$ are AE constants)

Techniques for spectral analysis of AE signals allowing finding out the mechanisms of fracture nucleation and development in alloys are known. They are applicable for similar investigations of composites. However, in this case it is necessary to specify that the optimum frequency band of AE device (generalizing published data) is 0,1 …0,5 MHz. In this interval the matrix generates AE signals, caused by fracture, in the range 0,09…0,18 MHz, approximately, fibers delamination – in the range 0,2…0,31 MHz and their failure – in the range higher than 0,31 MHz. A valuable achievement of these researches is the confirmation that the dispersion and attenuation of AE waves in composites essentially influence AE amplitudes even for short distances of their transmission inside a specimen. If this fact is ignored, significant divergences in test results may be observed.



a *b*

Figure 3: Response characteristics of AE signals obtained for points A (*a*) and B (*b*) of the *f* - *P* curve (see Figure 1) during pulse sounding of composite group II specimens.

The third criterion is based on the method of AE sounding of composite specimens. It consists in the following. An electric pulse from the calibrator unit of the AVN-3 device is submitted to a piezoelectric transducer [5], which actuates mechanical calibrating pulse. Recording the change in amplitude-frequency response of this pulse after its transmission through the damaged material, we estimated the damage degree of the composite. The process of microcracking in composites caused by failure of the matrix, fibers and their interfaces at the stage of subcritical loading is somewhat similar to the above-mentioned processes.

Criterion 3 takes into account a degree of attenuation of amplitude-frequency response components of AE pulse during sounding of a composite by estimation the changes of the area S_i variation below the spectral function that is restricted by frequency band of piezoelectric transducer (in our tests it was 0,1…0,5 MHz).

It is assumed, that for undamaged composite this area is equal to S_0 (the experiments have shown that the scattering of S_0 is approximately within

±10%), then for any arbitrary point of the f - P curve the current value of the area is less. Therefore, for the point corresponding to the beginning of the latent period (when stresses achieve σ^*) the value of S was $S = 0{,}82S_0 = S^*_2$, being accounted for real data scattering. On the basis of the experimental data obtained for the given type of composites (see Figure 3) we have established, that the minimal area under spectral function curves obtained at point P_{max} of f - P curves (see Figure 1) is $S = 0{,}53S_0 = S^*_1$ accounting the data scattering. Therefore, criterion 3 for considered composites is written as:

$$0{,}53S_0 \leq S \leq 0{,}82S_0. \quad (5)$$

CONCLUSIONS

The latent period of volume damages accumulation in composite materials begins from the moment of sharp increase in the amplitudes of AE signals and satisfies the criterion condition $\sigma^* \geq \alpha\sigma_{max}$.

The sum of AE signals amplitudes adequately describes the formation and growth of internal damages. For this reason, by referring it to the volume where fracture occurs, we can determine the beginning of critical stage of damaging by the relation $\Sigma A_i / V \geq \xi^*$.

The volume damage of composite materials considerably affects the attenuation of AE. This enables us, by comparing the areas below the curves of spectral functions of undamaged and loaded composites and by using the relation $S^*_1 \leq S \leq S^*_2$, to quantitatively estimate the subcritical state of accumulation of volume damages.

REFERENCES

1. Wevers M. (1997) *NDT Int*. **30**, 99.
2. Andreykiv O.Ye, Lysak M.V., Serhiyenko O.M. and Skalsky V.R. (2001) *Engng. Fract. Mech.* **68,** 1317.
3. Andreykiv O.Ye., Skalsky V.R., Serhiyenko O.M. (2001) *Materials Science* **37**, 106.
4. Andreykiv O.Ye., Skalsky V.R. (2001) *Mashynoznavstvo* **4-5,** 7.
5. Skalsky V.R., Augutis V.N., Vaynman A.B. (2001) In: *Collect. of Sci. Papers of Karpenko Phys.- Mech. Int. of Nat. Acad of Sci. of Ukraine* "Physical methods and facilities for environment, materials and products controlling" **6,** 77.